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Study of EEJ currents, fields and drifts over Thumba, India

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Abstract : The region of the ionosphere lying between 80 to 200 kms has been considered for discussion. The electric field driving the EEJ currents has been computed and studied under certain restrictive assumptions. A dip angle dependence of vertical polarization field is found out. The altitude variations of polarization electric fields have been studied using data of a quiet day of $F_{10.7} = 98.4$ at 11.00 hours IST measured by rocket borne experiments supplied by PRL, Ahmedabad. $E_{\parallel}$ has been taken to be 0.5 mV/m. The altitude structure of EEJ current and drift using the above data has also been discussed and the calculated values are found to be consistent with the experimental values.

Keywords : Local wind generated electrostatic field, primary electric field, magnetic coordinates, potential constancy.

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1. Introduction

The temporal and spatial variations of the EEJ using ground base magnetometer data have attracted wide attention of different workers. Also, rocket borne measurements in the EEJ have given valuable information on the height structure of the current density, polarization field etc. However, discrepancies still exist between theoretical and experimental values.

In the Peruvian sector, the maximum current density, according to Stening (1985), occurs at 104 kms altitude, which is better than Richmond's value of 103 kms (Richmond 1972), but it still falls short of the observed 107 kms. These observations and calculations are done at 12.00 hours LT. Again, the values obtained by Untiedt (1967) show maximum current at 100 kms which may be due to a few sets of observations.

In Indian sector over Thumba, Burrows and Sastry (1976) found the vertical electrostatic field peak at 104 kms.

Detailed investigation on the local wind generated electric fields and currents in the EEJ have been carried out by Reddy and Devasia (1981). Their calculations bring out a variety of height and latitude structure of the electric field and currents under different wind conditions. The large day to day variations in the structure of the EEJ may arise due to the effects of local wind which vary widely from time to time.

Reddy et *al* (1987) found the peak of the vertical polarization field at an altitude of 97 kms while the maximum phase velocity in the magnetic east-west plane occurs at 100 kms.

As pointed out by Reddy (1981) the electric field driving the EEJ are mainly due to the following causes :

(i) An electric field originating due to the dynamo action of the global scale wind system in the lower thermosphere (E-region) is the predominant driving field in quiet days,

(ii) Magnetospheric convection electric field penetrating to the low latitude ionosphere is mainly predominating on magnetically disturbed days,

(iii) An electric field originating due to local action of height-varying neutral wind with the ionosphere within the EEJ.

In this paper, we have considered case (i) only and the computed values have been compared to other equatorial EEJ models for a quiet day data ($F_{10\cdot7} = 98.4$) and have found the dependence of the vertical polarization field on the dip angle, which is not found in the available models.

The authors have assumed an altitude independent east-west primary electrostatic field (E_y) to be applied to a highly conducting region around the magnetic equator. This field gives rise to a large vertical polarization field (E_z) where X-axis is assumed to be along the magnetic south, Y-axis along east (along dip equator) and Z-axis upwards.

Recent experiments (Viswanathan et *al* 1987) have revealed that day time E_y values show a large day to day variations having an increase in forenoon and decrease in the afternoon hours.

In the present work, the EEJ currents, fields and drifts are considered almost at noon hours (11.00 hours 1ST). For $E_y = 0.5$ mV/m, these are consistent with the value deduced by Vikramkumar et *al* (1987).

Starting with this E_y, vertical polarization fields (Hall fields) and the Pedersen and Hall currents at different altitudes have been computed. Data of a quiet day of $F_{10\cdot7} = 98.4$ at 11.00 hours IST, measured by rocket borne experiment supplied by PRL, Ahmedabad (1987) corresponding to $E_y = 0.5$ mV/m have been used for computation.

2. Results and discussions

I. Vertical polarization field :

The primary electric field (E_y) is assumed to be static and parallel to the Y-axis having no X-component. Also, the Hall current is assumed to be entirely inhibited by the polarization of the medium in vertical direction along which the field is E_z. The Hall current, because of the relative mobilities of electrons and ions, flows in the direction perpendicular to both $\boldsymbol{E}$ and $\boldsymbol{B}$.

Let the electric field be

$$\boldsymbol{E} = E_y\hat{j} + E_z\hat{k}$$

where $\hat{i}$, $\hat{j}$, $\hat{k}$ are the unit vectors along X, Y and Z directions respectively. The magnetic field is

$$H = H\hat{h} = -H\cos I\,\hat{i} - H\sin I\hat{k}$$

where I is the magnetic dip angle. As in Baker and Martyn (1953) the component of $\boldsymbol{E}$ parallel and perpendicular to $\boldsymbol{H}$ are respectively given by

$$\boldsymbol{E}_0 = E\hat{h}\hat{h} = E_z\sin I\cos I\,\hat{i} + E_z\sin^2 I\,\hat{k}$$

$$\boldsymbol{E}_1 = -E_z\cos I\sin I\hat{i} + E_y\hat{j} + E_z\cos^2 I\hat{k}$$

Thus the current density is

$$\boldsymbol{J} = \sigma_0\boldsymbol{E}_0 + \sigma_1\boldsymbol{E}_1 + \sigma_2(\hat{h}\times\boldsymbol{E})$$

$$= [(\sigma_0-\sigma_1)E_z\sin I\cos I + \sigma_2 E_y\sin I]\hat{i} + [\sigma_1 E_y + \sigma_2 E_z\cos I]\hat{j}$$

$$+[E_z(\sigma_0\sin^2 I + \sigma_1\cos^2 I) - \sigma_2 E_y\cos I]\hat{k} \tag{1}$$

where σ_0 = parallel conductivity, σ_1 = Pedersen conductivity, and σ_2 = Hall conductivity.

Since $\nabla J = 0$ so, J_z must be of the order of 10^{-2} of the horizontal current which is negligible (Maeda 1977). Taking $J_z \approx 0$ one gets

$$E_z = \frac{\sigma_2}{(\sigma_0\tan^2 I + \sigma_1)\cos I}E_y \tag{2}$$

This value of E_z differs from that of Sugiura and Cain's model by a factor $1/\cos I$ (Sugiura and Cain 1966).

This equation shows the dependence of vertical polarization field (Hall field) on the magnetic dip angle.

From eq. (2) the Hall field at dip equator ($I=0$) is

$$E_z = \frac{\sigma_2}{\sigma_1} E_y \tag{3}$$

Thus the vertical polarization field is σ_2/σ_1 times the original horizontal field. Also, Fejer (1981) showed the validity of eq. (3) close to the dip equator at an altitude below 110 kms.

Figure I shows the variation of σ_2/σ_1 with altitude. The ratio of σ_2/σ_1 is extremely large in the region near 98 kms attaining a value of 28.67. Thus the

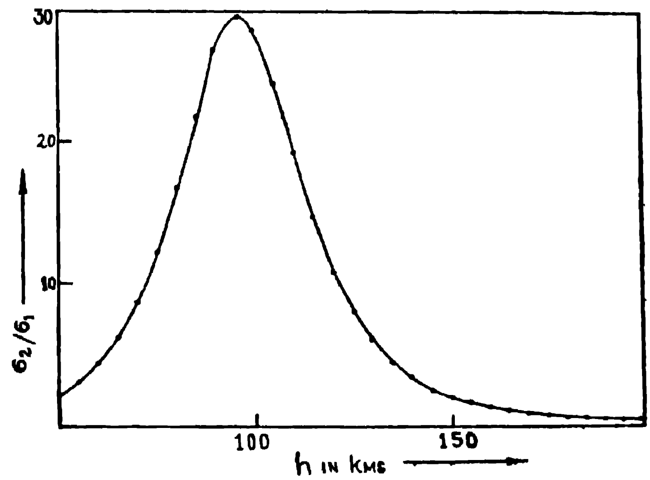

Figure I. Altitude variation of σ_2/σ_1.

vertical polarization field changes proportionately with σ_2/σ_1. E_z exhibits variation with height similar to that of σ_2/σ_1.

Figure 2 shows the height structure of E_z. The maximum of E_z occurs at a height of 98 kms as in the case of σ_2/σ_1 and also the magnitude of E_z is 14.38 mV/m for an east-west electric field E_y of 0.5 mV/m. But Reddy (1981) has theoretically deduced the polarization electric field for an assumed east-west electric field of 0.3 mV/m where the maximum occurs at 100 kms and the magnitude of $E_z=8$ mV/m (Figure 1, Reddy 1981).

Again, Reddy et *al* (1987) have shown that the maximum of E_z, deduced from the measurements of phase velocity and electric fields at Thumba, occurs at 97 kms.

Also from eq. (2), the magnitude of E_z changes at different places with different coordinates. It decreases with the increase of I and approximates to straight lines within 80 and 140 kms as shown in Figure 2. For $I=10^\circ$, E_y is maximum at 84 kms, whereas for $I=0^\circ$, the maximum occurs at 98 kms. But for other values of I the maximum does not occur above 80 kms.

From the aforesaid discussions, it is clear that the polarization field is a major factor and plays very important role in constructing EEJ current although the horizontal field is small. At places of higher dips the polarization field decreases

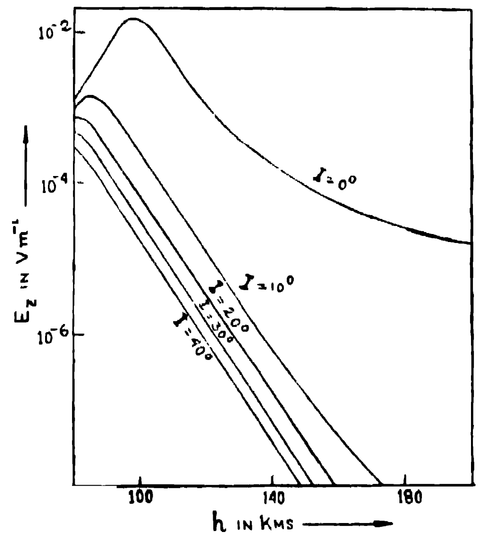

Figure 2. Altitude structure of polarization electric field E_z.

and becomes negligibly small. It is seen that the polarization field has a large variation with height as that of Reddy (1981).

II. East-west (Pedersen) and vertical (Hall) currents in EEJ :

We recall eq. (2) which gives the vertical polarization current (Hall current) as

$$J_H = \sigma_2 E_z = \frac{\sigma_2^2}{(\sigma_0 \tan^2 I + \sigma_1) \cos I} E_y \tag{4}$$

Also, the horizontal current (east-west) is the Pedersen current and is

$$J_P = \sigma_1 E_y \tag{5}$$

Thus, the total, electrojet current (J) is the sum of the Pedersen and Hall currents (Sugiura and Cain 1966, Stening 1985).

Hence,

$$J = \left[\sigma_1 + \frac{\sigma_2^2}{(\sigma_0 \tan^2 I + \sigma_1) \cos I}\right] E_y \tag{6}$$

The quantity inside the parenthesis [ ] of eq. (6) is the effective conductivity of a given region.

Now at the dip equator, eq. (6) for the total current reduces to

$$J=\left(\sigma_1+\frac{\sigma_2^2}{\sigma_1}\right)E_y=\sigma_3 E_y \tag{7}$$

where σ_3 = Cowling conductivity.

The eq. (7) gives the Sq current on the dip equator around noon hours i.e. EEJ currents as that of Maeda (1977) and Sugiura and Cain (1966). Figure 3 shows the altitude variation of Pedersen current, Hall current and the total EEJ current.

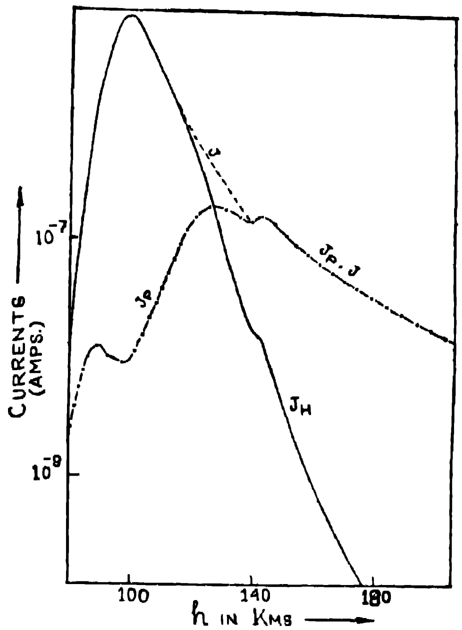

Figure 3. Altitude structure of Pedersen, Hall and total EEJ current density.

To deduce the east-west current using eq. (5), we have taken the electron density profile from rocket experiments supplied by PRL for 11.00 hours local time. The electron density profile is shown in Figure 4. It increases at large rate upto about 100 kms above which the increment is very slow becoming to some extent constant above 145 kms. There is no peak in our electron density profile (Indian sector) which is different from that due to flights of Maynard (1967).

In our calculations for east-west current density (J_P) at dip equator we have got the peak of magnitude 0.18 $\mu A/m^2$ at 128 kms for an east-west electric field of 0.5 mV/m. But Reddy (1981) has found out the peak at an altitude of about 104 kms where the magnitude is of the order of 5$\mu A/m^2$ (Figure 1, Reddy 1981) for an assumed east-west field of 0.3 mV/m. Although these are not consistent, yet the calculations are based on experimental data as supplied by PRL. Interesting to note that two other peaks occur at 90 kms (0.012 $\mu A/m^2$) and 142 kms (0.15 $\mu A/m^2$).

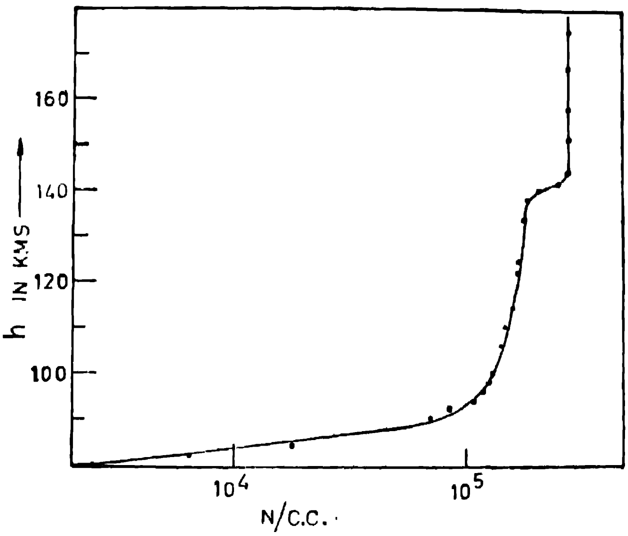

Figure 4. Altitude variation of electron density *N*.

The vertical polarization current (Hall current) J_H is maximum at 100 kms at dip equator, but in Peruvisn sector the peak is at 120 kms (Stening 1985) as that of Forbes and Lindzen (1976) although the amplitudes are different.

Regarding the total current density (J) from eq. (7) we have got the peak at an altitude of 100 kms and of magnitude 7.5 $\mu A/m^2$. The magnitudes of current density in our calculations are higher than that observed earlier where $J=4.2$ $\mu A/m^2$ corresponding to flight 20.07 (Stening 1985). In Indian sector following the electron density profile from flight 20.07 the peak of the maximum current was at 106 kms consistent with the second peak of Stening's model (Stening 1985). Although in that model there was another peak at 104 kms consistent with rocket results of Burrows and Sastry (1976). But according to the flights of Maynard (1967) the peak is obtained at higher altitudes (108-110 kms) from the maximum current in Peruvian sector although there was no peak in the electron density profile.

From the above discussion, it is clear that Pedersen current is quite smaller than Hall current. In the altitude range 80-120 kms the Hall current is so large that it appears to contribute solely to total EEJ current J. This result is consistent with the values appearing in most literatures which concludes that the EEJ currents in the E-region (mainly from 90-120 kms) consists of a small Pedersen current driven by the east-west electric field and a large Hall current driven by the vertical polarization field produced by the impeded Hall current driven by the primary east-west field (Baker and Martyn 1953, Reddy 1981). Above 120 kms J_H decreases rapidly and J is then mainly due to J_P. For this, the second peak of J coincides with the third peak of J at 142 kms.

3. Drift

(a) Vertical drift :

From above discussions it is apparent that Hall current due to vertical polarization field is the main constituent of the EEJ current. Again, the ratio ν_i/ω_i has been computed by the authors, where ν_i represents ion-neutral collision frequency and ω_i is the gyro-frequency for ions. It is seen from Figure 5 that at about 126 kms

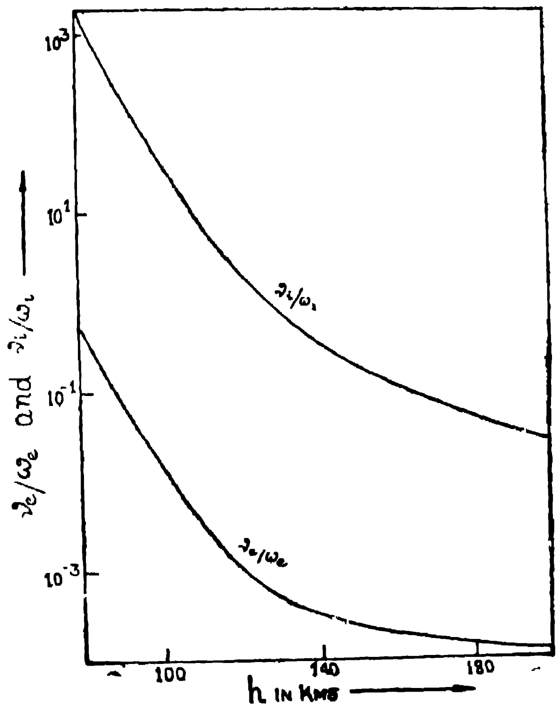

Figure 5. Altitude variation of ν_e/ω_e and ν_i/ω_i.

$\nu_i=\omega_i$ which was at about 130 kms by Rishbeth and Walker (1982). For the upper region (above 160 kms) $\nu_i \ll \omega_i$ and plasma movements perpendicular to the magnetic induction $\boldsymbol{B}$ are almost entirely controlled by the electric field $\boldsymbol{E}$. Under this circumstance the electromagnetic drift (Hall drift) of ions and electrons is given by $\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2}$ as used by Maeda (1970). Here the drift velocity reduces to E_y/B m/s similar to Kato (1973).

Again from Figure 6, it is seen that the Hall drift is almost constant (Variation of about 1 m/s only in between 80 to 200 kms) with respect to altitude. The present numerical value of this drift above 200 kms for dip angle 0° is a few m/s less than that of Woodman (1970) for dip angle 20° at Jicamarca. So, according

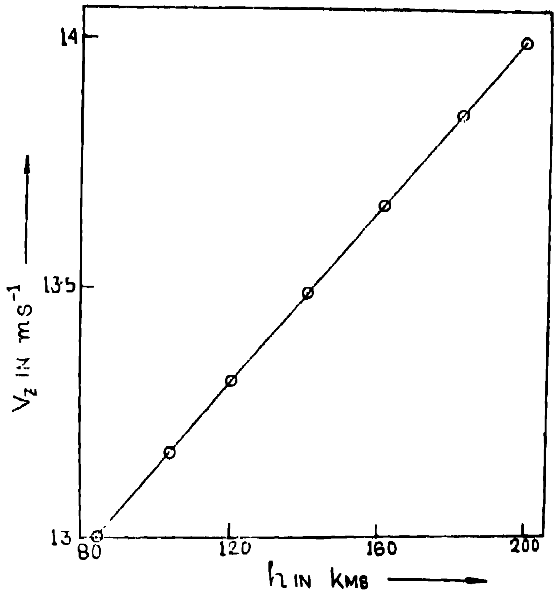

Figure 6. Altitude variation of vertical drift velocity V_z.

to the authors it would not be wise to compare these values for Indian sector below 200 kms altitude to that of Woodman. But the result in this work is consistent with that of Stening *et al* (1974) (i.e. 10 m/s). The numerical value deduced by the present authors, is 13 m/s. This constancy of vertical drift as a function of height is due to (i) the constancy of E_y as a function of height (Balsley 1973) and (ii) the potential constancy of the lines of force in the ionosphere (Jones *et al* 1986).

Thus, the drift changes due to the change in E_y which was 0.5 mV/m in the present calculation. Viswanathan *et al* (1987) have shown that the primary east-west electrostatic field (E_y) changes from time to time, day to day and from season to season. Thus, one may expect different upward drifts corresponding to the E_y value. As regards the constancy of the magnetic induction we have seen only a feeble change (about 0.024 Wb/m^2 from 80 to 200 kms) in B values.

(b) Horizontal drift :

A large vertical polarization field will result in the east-west drift of the electron which is identical with vertical drift (Maeda 1977).

The average electron velocity is given by Sugiura and Cain (1968) as

$$V_e = \frac{E_s}{B} \frac{1}{1+\nu_e^2/\omega_e^2}$$

where ν_e and ω_e are electron collision frequency and gyro-frequency respectively. The direction of V_e is west ward.

From Figure 5 it is seen that the ratio of ν_e/ω_e is small, so that ν_e^2/ω_e^2 may be neglected. The average electron velocity thus, reduces to $V_e = E_s/B$ m/s.

Again, from eq. (3), at equator, one has $E_s = \frac{\sigma_2}{\sigma_1} E_y$. Thus, the variation of electron velocity with altitude is practically due to the variation of the ratio σ_2/σ_1 as E_y is independent of height. The velocity attains a maximum (363 m/s) at about

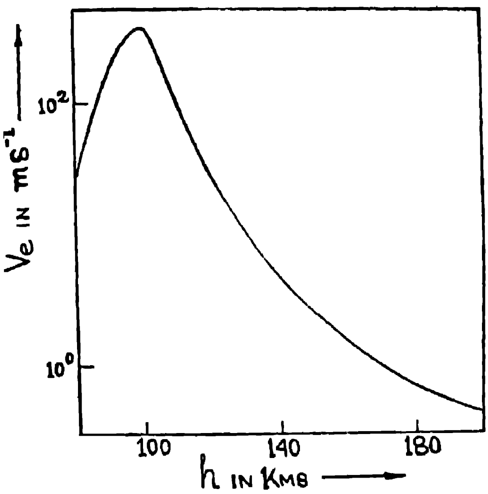

Figure 7. Altitude structure of horizontal drift velocity V_e.

100 kms (although σ_2/σ_1 is maximum at 98 kms) and then decreases (Figure 7). At an altitude of about 170 kms it is negligibly small.

4. Conclusions

The present theoretical work is based on available experimental data. For discrepancies in the magnitude of the EEJ current, the height of the maximum current peak and value of the drift velocities, more detailed data are required for a set of days including horizontal and vertical wind velocity which have not been considered in this work.

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